

THE SLOW ORBITAL EVOLUTION OF THE ACCRETING MILLISECOND PULSAR IGR J0029+5934

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ABSTRACT

The accreting millisecond pulsars IGR J00291+5934 and SAX J1808.4–3658 are two compact binaries with very similar orbital parameters. The latter has been observed to evolve on a very short timescale of ~ 70 Myr which is more than an order of magnitude shorter than expected. There is an ongoing debate on the possibility that the pulsar spin-down power ablates the companion generating large amount of mass-loss in the system. It is interesting therefore to study whether IGR J00291+5934 does show a similar behaviour as its twin system SAX J1808.4–3658. In this work we present the first measurement of the orbital period derivative of IGR J00291+5934. By using *XMM-Newton* data recorded during the 2015 outburst and adding the previous results of the 2004 and 2008 outbursts, we are able to measure a 90% confidence level upper limit of $-5 \times 10^{-13} < \dot{P}_b < 6 \times 10^{-13} \text{ s s}^{-1}$. This implies that the binary is evolving on a timescale longer than 0.5 Gyr, which is compatible with the expected timescale of mass transfer driven by angular momentum loss via gravitational radiation. We discuss the scenario in which the power loss from magnetic dipole radiation of the neutron star is hitting the companion star. If this model is applied to SAX J1808.4–3658 then the difference in orbital behavior can be ascribed to a different efficiency for the conversion of the spin-down power into energetic relativistic pulsar wind and X-ray/gamma-ray radiation for the two pulsars, with IGR J00291+5934 requiring an extraordinarily low efficiency of less than $\sim 5\%$ to explain the observations. Alternatively, the donor in IGR J00291+5934 is weakly/not magnetized which would suppress the possibility of generating mass-quadrupole variations.

Subject headings: binaries: general — stars: individual (IGR J00291+5934) — stars: neutron — stars: rotation — X-rays: binaries — X-rays: stars

1. INTRODUCTION

The accreting millisecond X-ray pulsar (AMXP) IGR J00291+5934 is a peculiar transient X-ray binary for two reasons. The first is that it is the fastest spinning known accreting pulsar, with a spin frequency of $\nu \sim 599$ Hz. Despite it being still far from the 716 Hz record holder J1748-2446AD (Hessels et al. 2006), IGR J00291+5934 has shown a measurable spin-up during one outburst in 2004 and spin down during quiescence which allows the determination of its spin evolution over few years timescale (Burderi et al. 2006; Patruno 2010; Papitto et al. 2011; Hartman et al. 2011). The second reason, which is also the main motivation of this work, is that when looking at its orbital parameters, IGR J00291+5934 is basically a twin system with the other well known AMXP SAX J1808.4–3658 (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998; see also Table 1 in Patruno & Watts 2012 for a comparison). IGR J00291+5934 was first discovered during an outburst in December 2004 (Shaw et al. 2005; Galloway et al. 2005) and it has been observed in outburst again in 2008 (Patruno 2010; Lewis et al. 2010; Papitto et al. 2011; Hartman et al. 2011) and 2015 (Sanna et al. 2015). Its 2008 outburst showed a peculiar behavior, with a first short outburst lasting ~ 5 days, followed within one month by a second 12 days long outburst (Patruno 2010; Hartman et al. 2011). The source has a radio counterpart (Pooley 2004) and its astrometric position has been determined with great accuracy (Rupen et al. 2004). The binary has an orbital period of 2.46 hr, so that its orbit is expected to evolve because of angular momentum loss from gravitational wave emission (see e.g., Paczyński 1971; Bildsten & Chakrabarty 2001). Its companion star has a minimum mass of $0.039 M_{\odot}$ with a detected optical counterpart both during outburst (Fox & Kulkarni 2004)

and quiescence (D’Avanzo et al. 2007; Torres et al. 2008; Jonker et al. 2008). In particular, careful modeling of the optical counterpart in quiescence has shown that the donor is almost certainly irradiated by a source of energy which is much more powerful than the quiescent X-ray luminosity available to the system. The irradiation of the donor from a pulsar wind is a particularly interesting feature because it has been suggested as the mechanism at the origin of the peculiar orbital evolution of SAX J1808.4–3658 (di Salvo et al. 2008; Burderi et al. 2009) which is expanding on a very short timescale of ~ 70 Myr instead of the expected billion years predicted by the theory of angular momentum loss from gravitational waves (Hartman et al. 2008; Patruno et al. 2012).

In this work we analyze the data from a new set of observations carried by the *XMM-Newton* observatory during the last July/August 2015 outburst of IGR J00291+5934. We focus on the orbital evolution of the system since the number of outbursts and the length of the observational baseline are now sufficient to measure the orbital period evolution of the binary. Since IGR J00291+5934 and SAX J1808.4–3658 share so many similarities it is plausible to expect a similar orbital period evolution for both systems and in this paper we test this hypothesis.

2. DATA ANALYSIS

The 2015 outburst of IGR J00291+5934 was first detected with the MASTER II robotic telescope by Lipunov et al. (2015) on July 24, 2015 at 05:42:03 UT. *XMM-Newton* observed the source on July 28, 2015 at 11:48:19 and ended its task on July 29, 2015 at 11:51:02 UT.

We used the European Photon Imaging Camera (EPIC) which is composed by two MOS CCDs (Turner et al. 2001) and a pn camera (Strüder et al. 2001) sensitive in the 0.1–12 keV range. In this work we use only the EPIC-pn data, which

are recorded in *TIMING* mode, with sampling time of about $29.56\mu\text{s}$, sufficient to clearly detect the accretion powered pulsations. The data are processed using SAS version 15.0.0, with the most up-to-date calibration files (CCF) available on September 2016.

Standard data screening criteria were applied in the extraction of scientific products with a 0.3–10 keV energy range selected and a net exposure of 72 ks (after removing solar flares and telemetry dropouts). Photons are extracted in a rectangular region with a width of 6 pixels centered around the RAW coordinate 38 and only when the PATTERN=0. The background is obtained from a region of the same size, at RAWX 28. The data are barycentered using the SAS tool *barycen* by using the source coordinates of [Rupen et al. \(2004\)](#).

The pulsations are folded in pulse profiles of 32 bins, with a length of ~ 500 -s each, using a circular Keplerian orbit and a constant pulse frequency. The first-guess ephemeris are taken from the 2004 outburst (see e.g., [Patruno 2010](#)) with the time of passage to the ascending node (T_{asc}) updated from [Kuiper et al. \(2015\)](#), which performed a first timing analysis of the 2015 outburst with *INTEGRAL* data.

3. RESULTS

Since the pulse profiles of IGR J00291+5934 are nearly sinusoidal, we define the pulse time of arrivals (ToAs) as the peak of the sinusoid of each profile. We then fit the ToAs with the software TEMPO2 (v. 2016.05.0; [Hobbs et al. 2006](#)) by using a constant pulse frequency plus a constant circular Keplerian orbit (ELL1 model). We then refine the ephemeris by iterating the procedure until convergence is achieved. We refer to the pulse frequency (observable) as distinct from the spin frequency since it has been shown that the X-ray flux has an influence of the pulse ToAs and might affect the determination of the correct spin frequency up to several tenths of μHz ([Hartman et al. 2008](#); [Patruno 2010](#); [Patruno et al. 2009](#)). We find a pulse frequency of $\nu = 598.89213099(6)$ Hz and no pulse frequency derivative is detected with $|\dot{\nu}| < 10^{-11} \text{ Hz s}^{-1}$ at the 95% confidence level.

To detect the evolution of the orbit we instead follow the procedure already outlined in [Patruno et al. \(2012\)](#), which is also used in [Hartman et al. \(2008\)](#); [di Salvo et al. \(2008\)](#); [Burderi et al. \(2009\)](#); [Hartman et al. \(2009\)](#); [Burderi et al. \(2010\)](#); [Sanna et al. \(2016\)](#), i.e., we select all four measured T_{asc} from the 2004, the double 2008 and the 2015 outbursts and we use the quantity $\Delta T_{\text{asc}} = T_{\text{asc},i} - (T_{\text{asc,ref}} + N P_b)$, where $T_{\text{asc},i}$ refers to the i -th outburst, N is the closest integer to $(T_{\text{asc},i} - T_{\text{asc,ref}}) / P_b$ and P_b is the orbital period. Since the best determination of P_b is made in 2004, we use that outburst as the reference one in our first set of calculations (see e.g. Table 3 in [Patruno 2010](#)). We use a polynomial expansion to describe the evolution of the time of passage through the ascending node:

$$T_{\text{asc}}(N) = T_{\text{asc,ref}} + P_b N + \frac{1}{2} P_b \dot{P}_b N^2 + \dots \quad (1)$$

In our analysis we calculate first the differential correction to the orbital period δP_b by fitting ΔT_{asc} with a linear function $\Delta T_{\text{asc}} = \delta P_b N$. The fit gives $\delta P_b = 3.266(2)$ ms with a $\chi^2/\text{dof} = 0.15/3$ (see Figure 1). The origin of the very small χ^2 indicates that the statistical errors on the fitted parameters are unrealistic. The 2004 and 2015 outburst have errors on T_{asc} which are a factor of 5–10 smaller than the two 2008 outbursts. Therefore when fitting a linear function there is little

Table 1
Time of Passage through the Ascending Node for IGR J00291+5934

Outburst	T_{asc} [MJD]	Stat. Error [MJD]
2004	53345.1619259	0.0000016
2008 (1st)	54692.0411119	0.0000018
2008 (2nd)	54730.5292226	0.0000015
2015	57231.8470383	0.0000006

Table 2
IGR J00291+5934 Orbital Solution

Parameter	Value	Stat. Error
T_{asc} [MJD]	57231.8470383	6×10^{-7}
P_b [s]	8844.07673	9×10^{-5}
\dot{P}_b [10^{-13} s/s]	(-5; 6)	(90% c.l.)
a_1 [lt-ms]	64.993	0.002
e	< 0.0002	(95% c.l.)
P_{epoch} [MJD]	57300	

contribution from the 2008 data points and the fit gives a very small χ^2 .

The linear trend is very evident, so we use the best-fit δP_b to correct the orbital period. We then re-analyze the data published in [Patruno \(2010\)](#) for the entire data-set recorded for IGR J00291+5934 by folding the 2004, 2008 and 2015 data with the new orbital period and fitting the ToAs of each of the four outbursts with a Keplerian orbit where P_b is now fixed as well as the projected semi-major axis of the orbit and we fit only T_{asc} . This gives a new set of improved T_{asc} which we report in Table 1. We also tried to detect variations of the projected semi-major axes of the orbit a_1 . The four a_1 show no trend and are well fit by a constant ($\chi^2/\text{dof} = 4.2/3$).

We then inspect the new ΔT_{asc} to see whether residual trends are observed. For example, in SAX J1808.4–3658 a clear polynomial trend is observed ([Patruno et al. 2012](#); [Hartman et al. 2008](#); [di Salvo et al. 2008](#)) which is interpreted as an expansion of the orbit. In IGR J00291+5934 the residuals show instead very little structure, which is indicative of a very slow variation of the orbit. The data can indeed be well fitted with a constant consistent with zero. A fit with a quadratic polynomial gives both the linear and quadratic term consistent with zero (see Fig. 2) with a $\chi^2 = 0.18$ for 2 degrees of freedom. We therefore can set a 90% confidence interval for any orbital period derivative of $-5 \times 10^{-13} < \dot{P}_b < 6 \times 10^{-13}$. This means that the orbital evolution timescale of IGR J00291+5934 is at least $\tau > \frac{P_b}{\dot{P}_b} \sim 0.5$ Gyr. The final orbital ephemeris of IGR J00291+5934 are reported in Table 2.

As a further test we also combined all the data from 2004 up to 2015 in a single sequence of ToAs and fitted a Keplerian orbital solution with a \dot{P}_b term with TEMPO2. The orbit can be phase-connected because the total number of cycles observed is $N_{\text{cycles}} \sim 40,000$ and the initial error on our orbital period is $\sigma_{P_b} = 0.002$ s (the 2004 orbital period, see [Patruno 2010](#)) so that $\sigma_{P_b} \lesssim P_b / N_{\text{cycles}} \approx 0.2$ s. We stress that the pulse frequency (and its first time derivative) are very weakly covariant with the Keplerian parameters, so that any unmodeled trend in the neutron star spin is not affecting the determination of the orbital solution. The results are fully compatible within one sigma with those reported in Table 2 and give also compatible statistical uncertainties and confidence intervals.

4. DISCUSSION

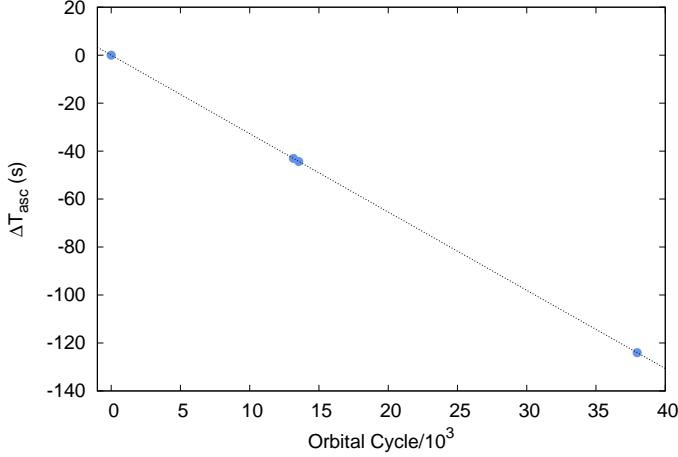


Figure 1. The differential corrections to the time of passage through the ascending node found when using the value of T_{asc} as reported in [Patruno \(2010\)](#). A linear trend (dotted line) is visible and can be well fitted by shifting the orbital period by ~ 3.3 ms. The error bars of the data are smaller than the symbols used.

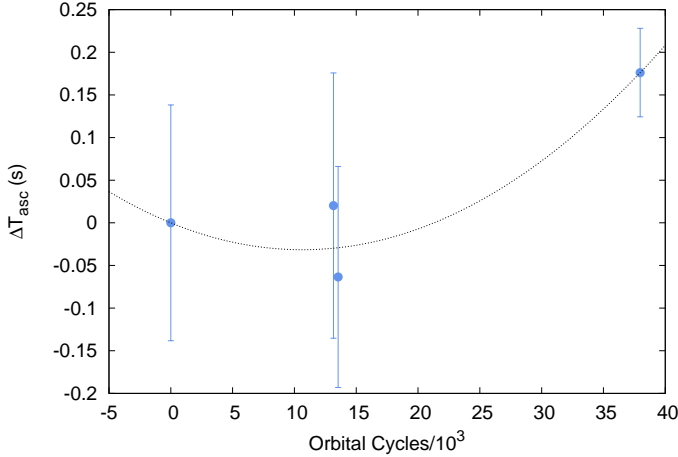


Figure 2. The differential corrections to the time of passage through the ascending node after correcting P_b . A constant function fits well the data and a quadratic polynomial (dotted line) provides upper limits on the presence of an orbital period derivative $-5 \times 10^{-13} < \dot{P}_b < 6 \times 10^{-13}$ (90% confidence interval).

The orbital evolution of IGR J00291+5934 proceeds on a timescale > 500 Myr which is in line with the expectation of a binary evolving via angular momentum loss caused by gravitational wave radiation. Indeed in this case the evolutionary timescale is ([Paczynski 1971](#)):

$$\tau_{\text{gw}} = 380 \frac{(1+q)^2}{q} \left(\frac{M_1 + M_2}{M_\odot} \right)^{-5/3} \left(\frac{P_b}{\text{days}} \right)^{8/3} \text{ Gyr.} \quad (2)$$

where $q = M_2/M_1$ is the binary mass ratio and M_1 and M_2 are the neutron star and donor mass. If we use reasonable values of $M_1 = 1.4 M_\odot$, $M_2 = 0.1 M_\odot$ then $q \approx 0.07$ and $\tau_{\text{gw}} \approx 7$ Gyr, consistent with the upper limits observed in this work. Although there is still the possibility that IGR J00291+5934 evolves on a timescale shorter than predicted (a factor ~ 10

is still allowed by our upper limits on \dot{P}_b), the binary seems to pose at the moment no challenge when compared to the expected behavior of binary evolution. However, when compared to the behavior of the AMXP SAX J1808.4–3658 the results presented in this paper become difficult to interpret. Indeed the “twin” system SAX J1808.4–3658 has shown an expansion of the orbit with a $\dot{P}_b \sim 3.5 \times 10^{-12}$, which is about one order or magnitude larger than our upper limits on IGR J00291+5934. The interpretation on why the orbits of these two systems behave so differently is puzzling if we look at all other measured parameters of the two binaries. SAX J1808.4–3658 shows indeed very similar properties: its orbit is 2.01 hours, its minimum companion star is $0.043 M_\odot$ ([Chakrabarty & Morgan 1998](#)) and the companion is irradiated by a powerful source of energy ([Homer et al. 2001](#); [Deloye et al. 2008](#); [Wang et al. 2013](#)). It has been proposed that, for both AMXPs, the source of extra irradiation comes from the spin-down power of the neutron star which might turn on during quiescence and irradiate with its powerful wind the exposed face of the donor star ([Burderi et al. 2003](#); [Campana et al. 2004](#); [D’Avanzo et al. 2007](#)). To understand whether such scenario is energetically feasible for IGR J00291+5934 we can assume two extreme cases, one with the minimum donor mass and with a neutron star mass of $M_1 = 2.5 M_\odot$ and the second with the maximum donor mass and $M_1 = 1.2 M_\odot$. With these parameters we can calculate the orbital separation and the donor Roche lobe radius for the two most extreme mass ratios. The fraction of intercepted pulsar radiation/wind can be estimated with the simple expression $f = (R_2/2A)^2$, where R_2 is the Roche lobe radius and A is the orbital separation. This fraction is nearly identical between IGR J00291+5934 and SAX J1808.4–3658, $f = 0.4$ – 1.0% , i.e., their donors are absorbing equal fractions of input energy.

Beside the excessive optical luminosity of the companion, there is further evidence (in both systems) that the neutron star is indeed losing power most likely due to magnetic-dipole radiation during quiescence. IGR J00291+5934 has been observed to spin-down in quiescence at a rate of $3 - 4 \times 10^{-15} \text{ Hz s}^{-1}$ ([Patruno 2010](#); [Papitto et al. 2011](#); [Hartman et al. 2011](#)) and SAX J1808.4–3658 is seen to spin down at a similar rate of $\sim 10^{-15} \text{ Hz s}^{-1}$ ([Hartman et al. 2008, 2009](#); [Burderi et al. 2009](#); [Patruno et al. 2012](#)). The assumption that the source of spin-down is the magnetic dipole radiation has lead to the indirect measurement of the neutron star magnetic field in both systems: $1.5 - 2.0 \times 10^8 \text{ G}$ for IGR J00291+5934 and $1 - 3 \times 10^8 \text{ G}$ in SAX J1808.4–3658 ([Hartman et al. 2008](#); [Patruno et al. 2012](#); [Papitto et al. 2009](#)). The spin-down power available in the two systems is therefore of the same order of magnitude, and it is within a factor 5 if we assume that the moment of inertia is the same for the two neutron stars. Other similarities between the two binaries include the observation of thermonuclear X-ray bursts ([Bozzo et al. 2015](#); [in ’t Zand et al. 1998](#)), the presence of H α emission line in outburst ([Roelofs et al. 2004](#), Kaper private communication) the detection of transient radio signals during outbursts ([Pooley 2004](#); [Gaensler et al. 1999](#)), a similar recurrence time for the outbursts (3–4 years for SAX J1808.4–3658 and 4–6 years for IGR J00291+5934) and comparable mass transfer and accretion rates ([Bildsten & Chakrabarty 2001](#); [Galloway et al. 2005](#)). It is safe to say that, with the exception of the orbital evolution, IGR J00291+5934 and SAX J1808.4–3658 have a tight match between all other observable quantities. It follows that if *any* of the observ-

Table 3
Comparison between observables in IGR J00291+5934 and
SAX J1808.4–3658

Parameter	IGR J00291+5934	SAX J1808.4–3658
Min. Donor Mass [M_{\odot}]	0.039	0.043
Max. Donor Mass ^A [M_{\odot}]	0.09	0.10
Donor Radius [R_{\odot}]	0.13–0.20	0.11–0.17
Orbital Period [hr]	2.46	2.01
Proj. Semi-major axis [lt-ms]	64.993	62.812
Outb. Recurrence Time [yr]	4–6	3–4
Irradiation ^B [10^{33} erg s ⁻¹]	~4–8	~1–10
L_{sd} ^C [10^{34} erg s ⁻¹]	7	2
Intercepted power f	(0.4–1.0)%	(0.4–1.0)%

^A the maximum companion mass is a 90% confidence level upper bound assuming $i = 26^{\circ}$ (Hobbs et al. 2006).

^B this parameter indicates the minimum power required to produce sufficient irradiation to explain the optical counterpart. For SAX J1808.4–3658 the irradiation luminosity is given for a range of distances 2.5–3.5 kpc

^C Spin down luminosity available in the system via $I\omega\dot{\omega}$. The table summarizes the properties of IGR J00291+5934 and SAX J1808.4–3658 relevant for the orbital evolution of the systems (see main text for an explanation and references).

ables listed above (see a summary in Table 3) is used to support a specific interpretation of the fast orbital evolution of SAX J1808.4–3658, the same should be true for IGR J00291+5934.

For example, the aforementioned over-luminous optical counterparts of IGR J00291+5934 and SAX J1808.4–3658 in quiescence have been interpreted as being generated by irradiation of the donor from the pulsar radiation/wind. In particular, the power injected by the pulsar into the companion of SAX J1808.4–3658 has been suggested to generate a large mass-loss (di Salvo et al. 2008; Burderi et al. 2009) which in turn would explain the large orbital \dot{P}_b . In this highly non conservative mass-transfer scenario about 99% of the mass transferred is lost in a stellar wind. IGR J00291+5934 has an over luminous optical companion, and this has been interpreted too as due to irradiation from the pulsar wind. A similar interpretation for IGR J00291+5934 seems difficult to reconcile with its slow orbital evolution that at the moment is compatible with a conservative scenario (i.e., no mass-loss). Indeed the variation of the orbital period of the binary as a consequence of a spherical wind loss from the donor is (Frank et al. 2002):

$$\frac{\dot{P}_b}{P_b} = -2 \frac{\dot{M}_2}{M_2} \quad (3)$$

If we use our upper limit on \dot{P}_b , then:

$$\dot{M}_c = \frac{1}{2} \frac{\dot{P}_b}{P_b} M_c \lesssim 10^{-10} M_{\odot} \text{ yr}^{-1} \quad (4)$$

which is about an order of magnitude smaller than proposed for example in SAX J1808.4–3658. To explain such dramatic difference in behavior between these two accreting systems we propose three possibilities.

A first possibility is that there are two different mechanisms operating in these binaries. There is a subtle difference in the optical behavior of IGR J00291+5934 with respect to SAX J1808.4–3658 during quiescence that was reported by Jonker et al. (2008). If the optical excess can be entirely ascribed to the donor being irradiated then, during

quiescence, an optical modulation with a peak at the neutron star inferior conjunction (phase 0.5) should be observed. This was indeed the case for IGR J00291+5934 as reported by D’Avanzo et al. (2007) when using near-infrared observations. However, Jonker et al. (2008) when analyzing further observations in the I -band (September 13 and 14 2006) found a sinusoidal modulation peaking at phase 0.34 ± 0.03 along with very large (~ 1 mag) optical flares. The conclusion of Jonker et al. (2008) was that a modulation with a period slightly different from the orbital period might be responsible for the sinusoidal modulation observed, in a way similar to superhumps observed in cataclysmic variables and other X-ray binaries. However, the (quasi)orbital modulation detected by Jonker et al. (2008) and D’Avanzo et al. (2007) has an amplitude of only a few percent, meaning that the bulk excess optical light still exceeds by 1–2 orders of magnitude the quiescent X-ray luminosity of the residual accretion disk. Given that any other observable quantity is almost identical in both AMXPs, we cannot support any other possibility with the existing observations.

The second possibility is that the mass-loss scenario in SAX J1808.4–3658 is not correct and that the orbital period derivative is caused by a different phenomenon. Hartman et al. (2008, 2009) and Patruno et al. (2012) proposed a scenario in which quadrupolar mass variations in the donor cause a variation of the orbital parameters due to spin-orbit coupling (Applegate 1992; Applegate & Shaham 1994). In that scenario the donor is required to have a large magnetic field for the effect to take place, and in SAX J1808.4–3658 it was estimated that a field of the order of 1 kG is necessary. The Applegate mechanism (or a similar one) is appealing because it might explain the observation in terms of an unseen magnetic field of the donor star (which, in the case of IGR J00291+5934 should be weakly or no magnetized). However, it is not clear whether such a mechanism can take place in a tiny donor star like those observed here and indeed several criticisms exist in the literature. The main objection to the model is that the formation of a mass quadrupole requires a certain amount of energy that is too large when compared to the nuclear energy budget of the donor or to the tidal dissipation in the system (see e.g. Brinkworth et al. 2006).

Given that the fraction of absorbed power f is identical in both AMXPs, the final possibility is that the irradiation of the donor proceeds in the two systems with different efficiency. For example, D’Avanzo et al. (2007) estimated that the power required to irradiate the donor of IGR J00291+5934 is 4×10^{33} erg s⁻¹ (SAX J1808.4–3658 requires a similar value, see Burderi et al. 2003; Campana et al. 2004), whereas the spin-down power available in the system is $L_{sd} = I\omega\dot{\omega} \approx 8 \times 10^{34}$ erg s⁻¹, where $I = 10^{45}$ g cm² is the moment of inertia of the neutron star, and ω and $\dot{\omega}$ are the angular frequency and its first time derivative (which come from observations). This requires that less than $\sim 5\%$ of the spin-down power is converted into energetic wind and X-ray/gamma-ray radiation. For SAX J1808.4–3658 instead, the spin down-power is 2×10^{34} erg s⁻¹ and therefore the efficiency required is of the order of 40% with a peak efficiency close to 100% (Patruno et al. 2016).

5. CONCLUSION

We have placed stringent constraints on the orbital evolution of the accreting millisecond pulsar IGR J00291+5934. We find an upper limit for the orbital period derivative which translates into an orbital evolution timescale larger than 0.5

Gyr. There is a substantial difference between this behavior and that of SAX J1808.4–3658, an AMXP with very similar orbital parameters and donor properties. We find that, if we want to explain the orbital evolution of both binaries with a mass-loss model due to irradiation of the companion, then the pulsar in IGR J00291+5934 is radiating power which is partially converted into winds and high energy photons with an efficiency of less than 5%. Alternatively, if the variations of the orbit seen in SAX J1808.4–3658 are due to spin-orbit coupling, then the donor star in IGR J00291+5934 should be weakly or no magnetized which would suppress the mass-quadrupole variations.

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